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Research article

Potential of *Miscanthus* grasses to provide energy and hence reduce greenhouse gas emissions

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Abstract – Using bio-fuels, such as bio-ethanol or bio-diesel in transportation, or biomass in power generation reduces CO_2 emissions as the carbon is fixed by the plants from the atmosphere and saves the equivalent fossil fuel. The perennial rhizomatous C4 grass *Miscanthus* has one of the highest energy intensities per hectare of land in Europe. Here we model the future potential of Europe to produce *Miscanthus* with four different future land use and climate change scenarios and conclude that up to 17% of Europe's current primary energy consumption could be provided by this bio-energy crop by the year 2080 but that inter-annual variation of crop yield can be more than 20%. We conclude that that the highest greenhouse gas mitigation from bio-energy can be achieved by growing a *Miscanthus* crop on existing fertile and degraded arable land and not on land with a currently undisturbed ecosystem.

Energy crops / biofuel / bioenergy / climate change / modeling: Miscanthus / Greenhouse gas emissions

1. INTRODUCTION

The global use of energy is increasing at the rate of 2–3% a year due to the rapid industrialization of the economies of South East Asia, Brazil, China and India. This has created a demand for fossil fuels that is progressively difficult to satisfy, leading to increased prices and a drive for their substitution by sustainable energy sources such as wind, tidal, solar and bio-energy crops. In addition to energy security, concerns about global warming and the international agreement of the Kyoto Protocol (1998) have led many countries to develop ambitious, near term policy objectives for bio-energy in the belief that it is a largely carbon neutral source of energy.

Bio-energy currently accounts for 13.4% of current world energy needs, mainly in Africa and developing countries where biomass is used for heating and cooking. Increasing bio-energy use to supplement the energy needs of Europe and other industrializing and post industrialization economies will the require the growing of bio energy crops on an large scale entailing changes to agricultural and forestry production to grow dedicated energy crops.

Hoogwijk et al. (2005) analyzed the use of biomass for 17 different scenarios and showed its "research focus" potential by 2025 to 2050 was between 67 Exa Joules (EJ) and 450 EJ whereas the "demand driven" potential was between 28 EJ to 220 EJ. The global technical potential of bio-energy is therefore large but to realize this high energy yielding crops would have to be found that were suited to growing conditions in each area. Sims et al. (2006) suggested that the perennial rhizomatous C4 grass *Miscanthus* has a higher energy yield per hectare (204 GJ ha^{-1}) of energy than other bio-energy crops such as short rotation coppice willow or poplar (168 GJ ha^{-1}), bio-diesel from oil seeds (27 GJ ha^{-1}) or ethanol from starchy or sugary biomass (14–114 GJ ha^{-1}). *Miscanthus* is a native of SE Asia and occurs naturally in various genotypic forms in a wide variety of climatic conditions from Manchuria to islands in the S Pacific and although it is a C4 plant it can survived severe winter condition in botanical gardens in northern cities such as Copenhagen and Chicago. Its potential as a bio-energy crop has been demonstrated by field experiments over the last two decades in Europe in a wide variety of soil and climatic conditions from Sweden in the North to Portugal and Greece in the South (Lewandowski et al., 2003a). These tests have

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shown that *Miscanthus* genotypes can provide consistent high yields in a wide variety of soil and climatic conditions.

Tuck et al. (2006) demonstrated the wide geographical range of suitability of *Miscanthus* in Europe. Clifton-Brown et al. (2005) and Stampfl et al. (2007) used the *Miscanthus* growth model, MISCANMOD (Clifton-Brown et al., 2000a, 2005) to calculate the total dry-matter yields of *Miscanthus* for both water limited and irrigated scenarios considering various percentages of arable land in Europe using the mean meteorological conditions for 1960–1990. They did not look at future climate scenarios nor did they consider inter-annual variation of yield. These studies estimated the gross energy yield but did not perform life cycle analyses for either energy or greenhouse gas emissions.

Miscanthus has been cropped as a cellulose feedstock for paper mills in china for 30 years and in Europe it has started to be grown in economic farm scale trials to co-fire coal power stations using up to 15% biomass mixed with the coal. Trials of its suitability as a standalone fuel have indicated that it can burnt in chipped form using technology used for woody biomass (Lewandowski et al., 2003b). Several authors have made life cycle analyses based upon field experiments (Lewandowski et al., 2003a; Heaton et al., 2004; Clifton-Brown et al., 2007; St Clair et al., 2008) that show for a 15 year crop life that the fixed energy cost is 9 GJ ha^{-1} y^{-1} with an incremental cost of 2 GJ Mg^{-1} of harvested *Miscanthus* dry matter grown using current micro-propagation technology and co-fired in a large coal fired power-station. This would reduce to 2 GJ ha^{-1} y^{-1} fixed energy cost with an incremental cost of 1 GJ Mg^{-1} dry matter if the crop could be grown using rhizome propagation and used as a fuel locally.

Greenhouse gas emissions caused by growing *Miscanthus* as a bio-energy crop are partially related to the CO_2 emissions associated with the energy cost of production and the N_2O emissions from the use of nitrogen fertilizers and so can be calculated directly from the energy and fertilizer input. The other component related to the change in soil organic carbon. Each land use reaches soil carbon equilibrium in 60–75 years which depend on the meteorological conditions for the rate of decomposition, the existing soil organic matter and the rate of carbon input which in turn depends on the vegetation and the harvested vegetable matter. Changes from the initial equilibrium to another in this time-frame, suggests an e-fold time constant for the change of around 20 years (Odell et al., 1984). *Miscanthus*, has a soil carbon equilibrium that is similar to grasslands and prairie grasslands of between 80 to 90 Mg ha^{-1} (Clifton-Brown et al., 2007; Kahle et al., 2001; Hansen et al., 2004; Beuch et al., 2000). This suggests that to avoid net soil carbon emissions *Miscanthus* should not be cropped on soils with initial carbon content greater than 90 Mg ha^{-1}, however, if grown on soils with a lower initial organic carbon content will result in a net accumulation of soil organic carbon.

As *Miscanthus* is has a high energy yield per hectare and has a relatively low energy input cost compared to other bio-energy crops, predicting its yield will represent the upper limit of bio-energy production in Europe. Here we describe how the MISCANMOD model, is encapsulated in a Fortran program that is used to predict *Miscanthus* yields for individual years on a grid spanning the European Union 27 countries. Simulations are run for four future climate scenarios (Intergovernmental Panel on Climate Change, 2001) predicting potential bio-energy yields for the European Union 27 as well as the inter-annual variation in this yield.

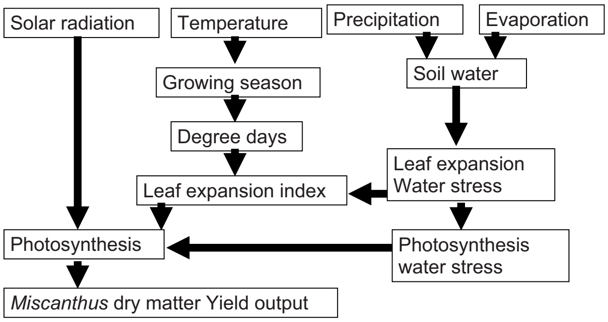

Figure 1. Block diagram of MiscanFor plant growth module showing the major data input, calculation stages and outputs.

2. MATERIALS AND METHODS

The MISCANMOD model was parameterized using crop experiments in Ireland (Clifton-Brown et al., 2000a, 2005). It was written in EXCEL^{TM} and based upon the Monteith (1977) method for photosynthesis and leaf expansion. Here we rewrite the model in FORTRAN adding a water stress calculation (Arnold and Foher, 2005) including plant physiological stages including water deficit induced senescence (Clifton-Brown et al., 2002) (Fig. 1). To verify the model was functional the EXCEL^{TM} and the FORTRAN models were run on the same data sets and the results compared by a linear regression. The new water stress function was testing by running the model on data sets from experimental plots with a known water deficiency and the day of onset of observed water stress through either a break in the height or leaf index measurement time series was compared in an ANOVA test to modeled soil water deficit.

This plant growth model is encapsulated in a FORTRAN geographical grid model (Fig. 2) that runs spatially at 0.5 degree resolution for which historical meteorological data is available on a 0.5 degree grid worldwide (Mitchell et al., 2004). This is interpolated in the European area from 500 to 1-200 weather station data at varying geographical locations from 1901–2002. United Nations Food and Agriculture organizations soil data is available worldwide on a 0.1 degree grid (Global Soil Task Group, 2000). From this fine grid the predominant soil property in each 0.5 degree meteorological grid is extracted using a geographical information system ($\text{ArcGIS}^{\text{TM}}$) to provide the field capacity and wilt point data, resulting in a 5,273 grid blocks model of Europe to predict bio-energy crop yields.

The monthly maximum and minimum temperature, frost days, rain days, average cloud cover and precipitation are read at 0.5 degree resolution. The global solar radiation is calculated using latitude, day of year, water vapor pressure and

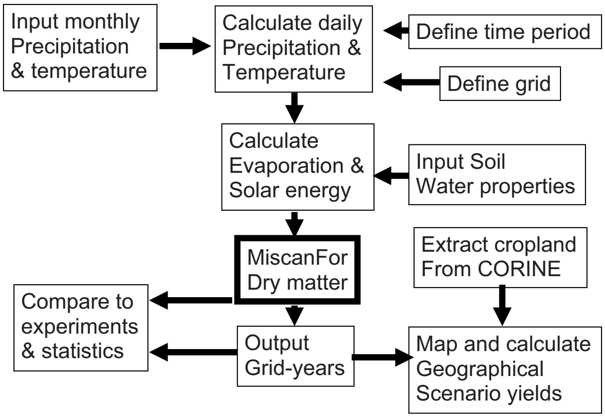

Figure 2. Block diagram of the MiscanFor model system showing the methodology for the meteorological data input from the Climate Research Unit historical and future scenario (Mitchell et al., 2004) and the soil moisture content data from the Food and Agriculture Organization soil properties data base, the function of the plant growth model in providing the *Miscanthus* yield estimates, the use of the land use data from the CORINE (2000) data base and available arable land from Rounsevell et al. (2005, 2006) for each climate scenario.

average cloud cover using the SWAT (Arnold and Foher, 2005) method. The potential evapo-transpiration is calculated according to Thornthwaite and Holteman (1939) and modified to match the Penman – Monteith potential evapo-transpiration using the UEA/CRU method to correct Thornthwaite for annual rainfall.

MiscanFor calculates the actual evapo-transpiration using a three component model that modifies the potential evapo-transpiration first by surface water evaporation then plant transpiration based upon the soil moisture content and the leaf area index, and finally evaporation from the soil based upon the soil capillary pressure. The actual evapo-transpiration and precipitation are then used to determine the daily soil water deficit for each year and grid point. The daily soil water deficit is used to calculate the down-regulation factor for leaf index expansion and photosynthesis. Mean temperature is used to calculate the beginning and end of the growing season (Clifton-Brown et al., 2000a). The leaf expansion and photosynthesis model, following Monteith (1977), with parameters determined by Clifton-Brown et al. (2000a), is then run to calculate the leaf index. This is then combined with solar radiation and the photosynthesis rate to calculate the above ground dry matter production for each day, which is summed for each year and grid point. The results can be output as daily or annual time series.

The MiscanFor model was calibrated using daily growth experiments in Ireland (Clifton-Brown et al., 2000a), Germany (Kahle et al., 2001), Denmark (Jorgensen, 1997) and the Netherlands (Van der Werf, 1993) with monthly measurements of yields and the actual site specific daily meteorological time series and using annual yields form other crop experiments in Sweden (Clifton-Brown et al., 2001), Portugal (Clifton-Brown et al., 2001), Greece (Danalatos et al., 2006), Italy (Cosentino et al., 2007) and England (Price et al., 2004) using monthly meteorological time series from the (1901–2000) Climate research Unit 0.5 degree data base (Mitchell et al., 2004).

To validate the model the outputs were also compared to field experiments in two ways. The MiscanFor module was run using the site specific metrological data and the measured soil parameters and the daily incremental crop yield was compared to incremental harvests made during the crop experiments. Then the total model was run using the Climate Research Unit 0.5 degree grid meteorological data for the year of the experiment and using the extracted grid soil data. The harvestable yield for each of the grid blocks that contained an experimental site was then compared to the experimental data.

The MiscanFor model was designed to create data to be converted to rasters for visualized as maps. MiscanFor also outputs the mean and standard deviation of any parameter such as temperature or precipitation or results such as leaf index or dry-matter yield over specified time intervals for each grid block. Historically the mean 1960–90 climate is used as the base case for all future climate change scenarios and this mean climate had been used to calculate *Miscanthus* yields in previous studies. Here we run the model for each year from 1960 to 1990 using the actual annual temperature and precipitation time series and then calculate the mean and standard deviation of the *Miscanthus* dry matter yields for each grid block for the 1960–1990 period. This standard deviation for each grid block was used to calculate the potential yield range of yields that could be expected for each future time slice/climate scenario/grid block.

The MiscanFor model was run using the 0.5 degree grid of future climate scenario data from Mitchell et al. (2004) which provides climate projections for the four international Panel on Climate Change emission scenarios for the period 2000 to 2100 (A1F1 (Global economic, fossil fuel intensive), A2 (Regional economic), B1 (Global environmental) and B2 (Regional environmental)). Yield outputs are compared for time slices at 2020, 2050 and 2080. The geographical information system, ArcGIS$^{\text{TM}}$, was used to extract the percentage of arable land to a 0.5 degree grid of per cell from the CORINE (2000) land use data base with a one minute grid resolution. This enables the total dry-matter yield per half degree grid block to be determined using 10% of the arable land for both the base case scenario (1960–1990) and the three future time slices for each of the four scenarios.

Miscanthus range is limited by climatic conditions due to frost and extreme drought killing the plant. Algorithms were added to the program to calculate plant kill flags for both frost (at a soil temperature of –3.4 °C) and draught conditions (60 days of soil moisture below the wilt point) for the *M. x giganteus* genotype. If a plant was killed more that four times in 100 years in a grid block then, due to the 15 year crop life of this perennial grass, it was unviable. This kill flag enabled the geographic range of *Miscanthus x giganteus* to be determined for each climate scenario. Different *Miscanthus* genotypes have different tolerances to frost and drought and exist in SE Asia in climates that cover most European conditions so we did not use the limitations of *M. x giganteus* to constrain the calculated European energy yields. However if the energy input exceeded the energy yield of the crop or the soil organic

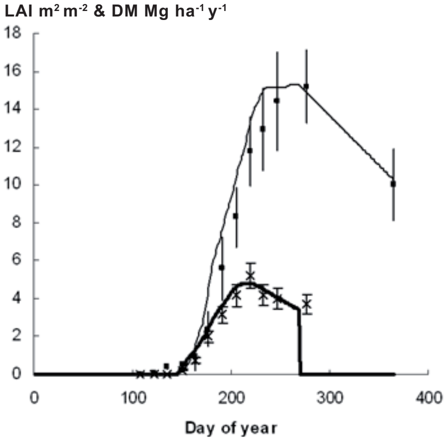

Figure 3. Comparison of the MiscanFor modeled leaf area index (LAI) in m^2 m^{-2} and Miscanthus dry matter yield (DM) Mg ha^{-1} y^{-1} to the experimental measurements with their standard errors is shown for 1995 at the Cashel, experimental plot 1 in Ireland, which is water limited.

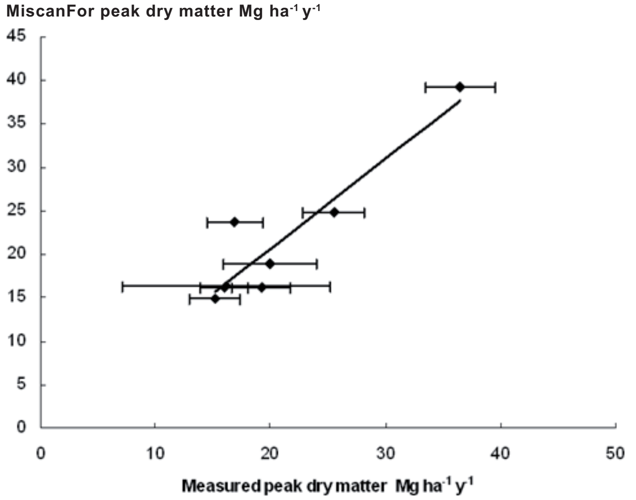

Figure 4. Comparison of the MiscanFor predictions of *Miscanthus* dry matter yield at peak harvest with the measured peak harvests at the experimental sites in Ireland, Sweden, Netherlands, Germany, Portugal, Greece and the UK, MiscanFor is run using actual site meteorological and soil data and the error bar on the experimental measurements shows the 95% confidence interval for all of the experimental plot measurements. The linear relationship is y = 1.033, $R^2 = 0.87$.

carbon of the block was more than 100 Mg ha^{-1} in the grid block the energy was considered unsustainable.

The dry-matter yield for each year and scenario were then multiplied by the arable land area in each of the grids and summed to calculate the average yield for Europe for each scenario. Blocks with unsustainable energy were eliminated but kill factors were not considered. The average yield for each year and scenario was then combined with the area available for bio-fuel crop production predicted by Rounsevell et al. (2005, 2006) for the four IPCC scenarios A1F1 (Global economic, fossil fuel intensive), A2 (Regional economic), B1 (Global environmental) and B2 (Regional environmental), with time slices of 2020, 2050 and 2080. We include the area that would be used to grow bio-fuel crops in the scenario plus the unused cropland that is not used for any other purposes to calculate the amount of dry matter that could be produced in each year scenario combination. This dry-matter was then converted to primary energy yield, using energy densities derived from Sims et al. (2006) and expressed as a percentage of the total European primary energy requirement for that year and scenario.

3. RESULTS AND DISCUSSION

Before modifying the model with the new soil water algorithm, the MiscanFor model was run on the same data set as the original EXCEL™ MISCANMOD and both *Miscanthus* dry yield output compared producing a linear match with $R^2 = 0.98$.

The new soil water capillary pressure method of evaporation down regulation was implemented in the model and produced a response curve that fitted the data on soil water published by Aslyng (1965). This new soil water MiscanFor predictions of plant growth were checked to experimental data sets from Portugal, Ireland, England and Spain that were known to have been grown in water limiting conditions. Statistically significant matches to the experimental monthly time series of LAI (leaf index), height and DM (dry matter yield) were obtained. Figure 3 shows the comparison for the 1995 Cashel Ireland data set. For all the data sets exhibiting water stress the ANOVA test of the onset of water stress observed in the experimental data (day of break in leaf index or height measurement time series) and the modeled day soil reaches wilt point was statistically significant $P > 0.02$.

A comparison of the MiscanFor model predictions using the with the new soil water calculation and the meteorological data and soil parameters measured at each of the experimental sites from Portugal, France, Italy, Germany, Greece, Netherlands, Denmark, Sweden, Great Britain and Ireland, resulted in a linear match the experimental yields with an $R^2 = 0.87$, $P < 0.005$.

When the full model was run for each year for the period 1960 to 1990, the mean peak yield for the entire European Union 27 for this period was 16.3 Mg ha^{-1} y^{-1} with a standard deviation of 2 Mg ha^{-1} y^{-1}. The same model run using the mean monthly meteorological conditions for each grid block for the same period gave a mean European peak yield of 18 Mg ha^{-1} y^{-1}.

The MiscanFor modeled dry-matter yield calculated using the A1F1, A2, B1 and B2 climate scenarios for the time slices1960–1990, 2020, 2050 and 2080 show yields falling in the South of Europe due to the reduction in growing season rain and increasing in the North due to the progressive warming with time. The A1F1 scenario displays the most extreme changes (Fig. 5).

Predictions of the area of land available to grow bio-fuel crops were available for four IPCC scenarios A1F1 (Global

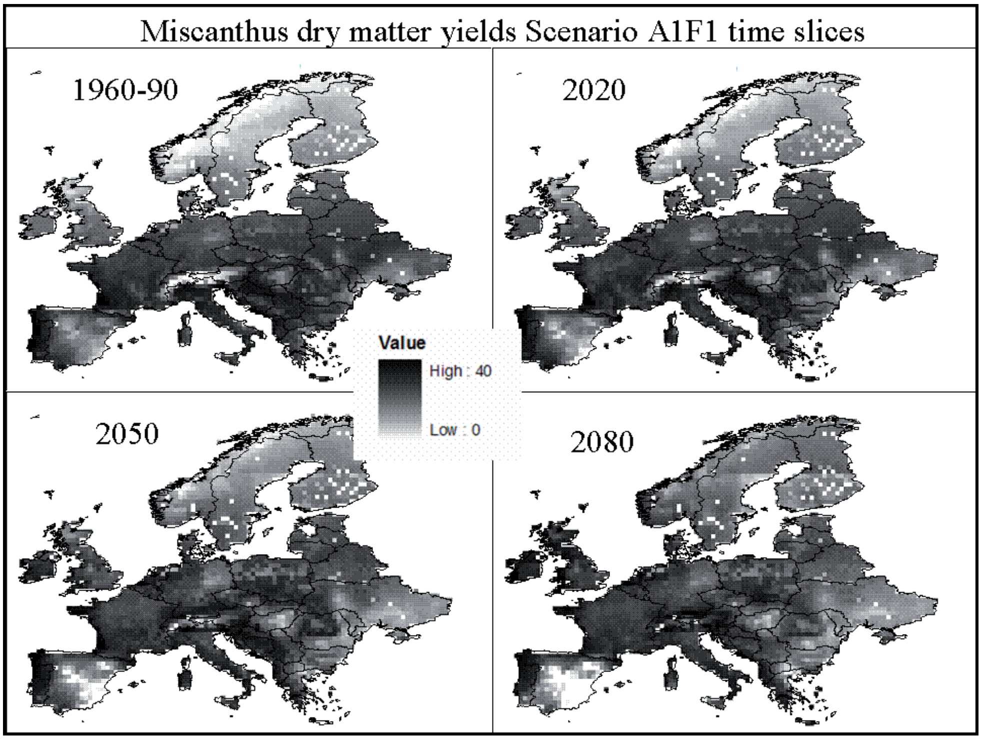

Figure 5. MiscanFor predicted yields of *Miscanthus* dry matter peak yields for the A1F1 IPCC scenario at time slices 2020, 2050 and 2080 compared to baseline case, which is the average of the period 1960–1990. The color scale is black 40 Mg ha^{-1}y^{-1} white is 0 Mg ha^{-1} y^{-1} of *Miscanthus* dry matter.

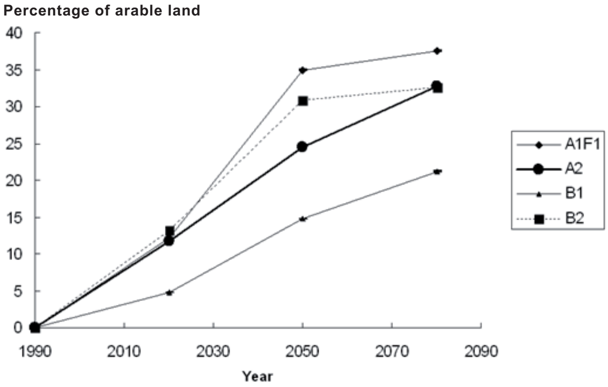

Figure 6. Area predicted by Rounsvell et al. (2005, 2006) to be used for Bio-energy crops for four International Panel on Climate Change scenarios: A1F1, A2, B1 and B2, expressed as a percentage of 1990 arable land for time slices of 2020, 2050 and 2080.

economic, fossil fuel intensive), A2 (Regional economic), B1 (Global environmental) and B2 (Regional environmental), for time slices of 2020, 2050 and 2080 from Rounsevell et al. (2005, 2006) expressed as a percentage of 1990 arable land shows an increase with time that varies with scenario, with up to 35% being available by 2080 for the A1FI scenario (Fig. 6). We include the area that would be used to grow bio-fuel crops in the scenario plus unused cropland that is not used for any other purposes. Rounsevell split the European area between EU 15 plus Norway and Switzerland and Eastern Europe, which includes Lithuania, Latvia and Estonia but excludes FSU (Former Soviet Union) states. We have summed them for the purposed of this model.

The mean peak *Miscanthus* dry-matter yield for the European Union 27 calculated from the MiscanFor yields in each grid block and using the spatial distribution of the arable land from the CORINE land use data base (2000) shows that the mean European yield increases with the warming trend for each scenario and that the increased yields in the North are partially offset by the decrease in yields in the South, controlled by the current distribution of arable land (Fig. 7). These yields are calculating excluding the non European Union countries of Norway Switzerland and Serbia.

Using 33% of the mean peak yield as the practical spring harvest yield (Clifton-Brown et al., 2007), the previously determined land available to grow bio-fuel crops and a *Miscanthus* dry matter energy intensity of 15 MJ kg^{-1} (allowing for 20% moisture) the *Miscanthus* contribution to European primary energy consumption is seen to rise to 17% by 2080 for the A1FI scenario (Fig. 8). The contribution is less for the other ‘less energy intensive scenarios’. To enable this data to be presented as a percentage we have compared the *Miscanthus* energy production to the primary energy consumption of Europe in 2000. The inter annual variation in the peak yield for the period 1960–1990 is superimposed on the A1FI yield to show the potential for yield variation from year to year.

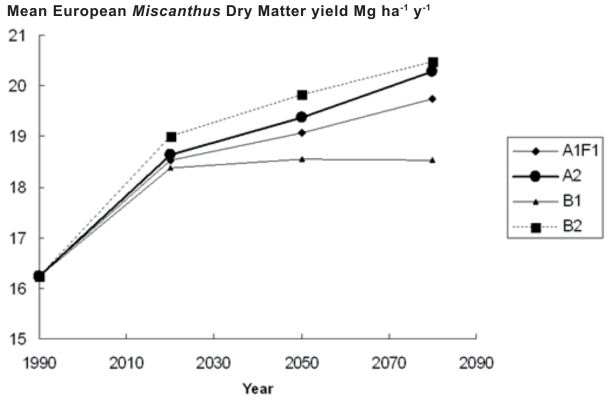

Figure 7. Predictions of the average European Union 27 peak yield of *Miscanthus* dry matter in Mg ha^{-1} y^{-1} for EU25 for four Intergovernmental panel of Climate Change scenarios, A1FI, A2, B1 & B2 and the time slices: base case 1960–1990, 2020, 2050 and 2080.

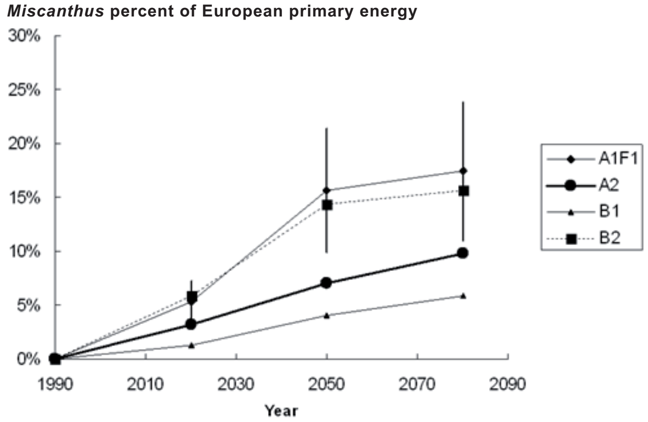

Figure 8. Prediction of the potential *Miscanthus* energy yield using the land area available from the Rounsvell et al. (2005, 2006) study and the MiscanFor simulated spring yields, expressed as a percentage of the year 2000 European primary energy use for the A1F1, A2, B1 and B2 climate change scenarios and base case 1960–1990, 2020, 2050 and 2080 time slices. The 95% confidence intervals of the predicted yield shown on the A1F1 scenario are based upon the 1960–1990 inter annual yield variation.

This development of MISCANMOD into the FORTRAN MiscanFor program has added functionality to the crop growth model to predict *Miscanthus* yields under water limited condition. This new model has improved the match to experimental data from the $R^2 = 0.54$ reported by Clifton-Brown (2001) to $R^2 = 0.84$ reported here. Using MiscanFor *Miscanthus* dry matter yields we show that up to 17% of Europe's energy needs could be provided from biomass by 2080 using the Rounsevell (2006) estimates land availability. However we also show that the inter-annual variation of that yield could range between 10 and 20% of energy requirements so that this needs to be considered in forward planning.

The model development work focused on the functionality of making forward predictions of energy yields on a continent wide scale and in the process of matching to experimental data showed that there many areas that he model could be improved in future work due to new data sets being published during the project. We have matched our model yield predictions to experiments growing the *Miscanthus x giganteus* sterile hybrid but have ignored the drought and frost tolerance of this genotype as other genotypes have displayed a wider range of tolerance. Future improvements to the model should include the physiological status of the plant from shoot to senescence to incorporate genotypic traits to make the model more flexible to incorporate the different strategies observed amongst genotypes for drought exposure and nutrient repartition to the rhizomes (Clifton-Brown et al., 2000b, c, 2002; Farrell et al., 2006). Published papers reporting on the experimental data sets used in this work had measured different radiation use efficiencies ranging from 1.1 to 3.2 2.4 g MJ^{-1} but our use of the new water stress algorithm modifying the single radiation use efficiency of 2.4 g MJ^{-1} of photosythetically active radiation, proposed by Clifton-Brown (2005) for above ground *Miscanthus* biomass, in MiscanFor provided a good match to the dry matter yield predictions $R^2 = 0.84$. In future work this could be improved by adding other factors such as temperature effects on the C4 photosynthesis.

Here we used the broad brush of European mean peak dry mater yield to calculate the energy yield, which is rigorous as long as the distribution of the energy requirements or the available land does not spatially change with time, so the model needs to be further developed to include this calculation at the grid level. We used a half degree grid to limit computing time. Whist this spatial resolution is appropriate for meteorological data, subject to changes in land surface topography, it less so for soil properties which can vary on a field scale. This was observes in *Miscanthus* field data sets such as Cashel Ireland. The soil moisture data was available at a 5 minute spatial resolution so in our spatial resolution matching to the meteorological half degree grid only the dominant value in the 36 soil grid blocks was chosen for the calculation of yields in the model grid. Future work should use the best spatial resolution available to improve the precision of the energy predictions as plant available water in the soil is a critical parameter in predicting yields.

The standard deviation of mean of the dry-matter peak yields calculated for the period 1960 to 1990 is 3.3 Mg ha^{-1} y^{-1}of the mean European peak yield of 16.5 Mg ha^{-1} y^{-1}. The 95% confidence interval of peak yields ranges from 9.9 to 23.1 Mg ha^{-1} y^{-1}. We show that using the mean meteorological condition for the same time period predicts a mean European dry matter peak yield of 18 Mg ha^{-1} y^{-1}showing that this method, used in previous studies (Clifton-Brown et al., 2005; Stampfl et al., 2007), overestimates the energy potential of *Miscanthus*. In our future scenarios we use the predicted mean meteorological conditions so our predictions will also be subjected to the same overestimation and future work will be required to generate representative meteorological time series for each scenario time slice. This will enable a more accurate mean yield to be predicted as well as the likely upper and lower limit of inter annual variation. Applying the standard deviation of energy yields for 1960–1990 to future scenarios indicates that the 95% confidence interval for our yield predictions will be ±40%. Design of *Miscanthus* and other bio-fuel projects will need to consider the variation in annual yields due to inter-annual weather patterns, both from the point of view of the minimum level of harvest and the requirement to be able to handle the larger ones.

Europe's ability to produce crops for use in as a bio-fuel is limited by the available land. St. Clair et al. (2008) demonstrated that the total GHG emissions from the growing of crops for the production of bio-fuels is not zero and it depends on the previous use of the land and the energy used in its production. In our model we have limited the area used for growing *Miscanthus* to arable land and to energy yields greater than the energy input (4 Mg ha^{-1}). Future work is required that calculates the green house gas emissions and energy use efficiency at each grid block to calculate the net energy production and the net greenhouse gas emissions. Here we have only considered the gross energy production but we have accounted for the moisture level of the fuel.

The Rounsevell et al. (2006) study to estimate the land that would be used for crops for bio-fuel and biomass was based upon the economic forces that drive the four representative IPCC climate scenarios. These vary from 35% for the global market and fossil fuel intensive A1F1 scenario to 20% for the local market environmentally driven B2 scenario for the 2080 time slice. Market forces in the A1F1 scenario produce the largest area for energy crops. In this study, only land that was used for arable farming in 1990 was considered for energy crops as it was assumed that crop yields in general will increase as the farming industry become more efficient and homogenized across Europe and make land available for bioenergy crops. Europe was considered in isolation and the impact the reduction of the availability of the European agricultural surplus to other areas would have on food prices or land use change in other areas was not considered. Future studies need to address the bio-energy – food competition for land use. In this study we have used these estimates of available land for each scenario and time slice. The distribution of arable land in Europe was taken from the CORINE 250 m resolution study and re-gridded as the percentage of arable land per 0.5 degree grid block. This loses resolution, especially in the coastal area but is a necessary compromise to enable the model to run the yield predictions in a reasonable time. In future the model could be run with smaller grid blocks for more detail over specific areas.

The spatial area distribution of arable land was used to calculate the average European *Miscanthus* yield for comparison purposed between the time slices and scenarios and clearly shows the increased yield in the Northern latitudes due to warming and the reduction in yields in the south due to less summer rainfall. The contribution of the bio-energy crop *Miscanthus* to Europe's primary energy needs in terms of the percent of energy is presented as the percent of energy use in the year 2000 rather than the actual energy predicted to be used in the IPCC scenario. This has been done for comparison purposes. It shows that there is the potential for *Miscanthus* to contribute up to 17% of Europe's primary energy by 2080 in the A1F1 scenario, but due to inter-annual meteorological variations, planners will have to have contingencies for alternative energy for the minimum of the 95% confidence interval of 10.9% of European primary energy needs.

4. CONCLUSION

We have described the improvements to a *Miscanthus* crop growth model and indicated the many ways that it could be improved in future work. In predicting the energy potential of the crop we have considered using only *Miscanthus* bio-mass as Europe wide it has the highest energy yield per ha of land, so the study represents the maximum possible energy yield with current plant and conversion technology. Future developments in crop yield and genotype improvement could increase this value. In addition if other bio-fuel crops are used in areas where their potential yield is higher than *Miscanthus* then the total energy production could be marginally higher. We have highlighted that in order to achieve maximum energy yield with minimum GHG emissions, only the arable land that is surplus for food production should be used for bio-fuel production and that natural ecosystems such as grasslands, heath lands and woodlands should not be used for this purpose. There are other sustainability considerations such as land fertility, water quality, biodiversity and visual amenity. It is likely that *Miscanthu*s will have a positive impact on land fertility as if grown on arable land will increase the soil carbon and due to its low nitrogen input requirements will have a positive impact on water quality. Although *Miscanthus* is a monoculture, significant biodiversity has been found in experimental stands so there is potential for a positive impact (Semere and Slatter, 2007a, b). The visual amenity could be an issue if we cover "Constable" like landscapes with 4m tall elephant grass but maybe the visual impact may be more acceptable than windfarms.

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